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Optimization of the conditions of cooperation of hybrid solutions of wind farms and solar farms for the area of Poland

Bernard Twaróg
b.twarog@pk.edu.pl | https://orcid.org/0000-0003-3150-1409
Department of Geoengineering and Water Management,
Faculty of Environmental and Energy Engineering,
Cracow University of Technology

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Abstract

With the increase in the share, with variable production of renewable energy sources in power systems, many studies and expert opinions have appeared in scientific research and the energy market to determine their optimal technological and locational cooperation. Modern Portfolio Theory (MPT) has often been applied in this context. However, some key aspects important in energy planning have not been included in these analyses. This article presents the use of the Markowitz model (Modern Portfolio Theory) in analyzing the hybrid co-option of selected energy sources, assuming two approaches that take into account gross potential and constraints imposed by technological capabilities. The goal is to determine the optimal value of the participation rate of wind farms and solar farms in the energy production co-op assuming the minimization of risk. The value of risk here is determined by a measure of dispersion for the delivery of a certain amount of energy. The results of the analysis are the determination of a map of optimal values of participation factors between the components of the hybrid energy complex for the area of Poland. Analyses were made for gross potential, showing the possibilities of maximum energy production, and for potential limited by technological possibilities. The study used data characterizing the potential of wind energy and solar energy and temperature. The data used in the analyses are publicly available for research purposes. The analyses were supported by graphs and commentary.

Keywords: power plant cooperation, hybrid power plants, wind power plants, PV power plants, MPT, optimization

1. Introduction

The feasibility and search for sustainable energy sources have become a priority due to the challenges posed by climate change and the depletion of fossil fuel resources. Renewable energy, including wind and solar power, plays a crucial role in transforming the energy sector toward a greener and more sustainable model. Energy derived from natural sources such as the sun, wind, water, and biomass is becoming the foundation for the future of energy. The use of renewable energy aims to reduce greenhouse gas emissions, lower environmental pollution, and enhance energy independence. Among renewable energy sources, wind and solar farms are gaining prominence. Wind farms harness the kinetic energy of the wind to produce electricity through wind turbines, while solar farms convert solar energy into electricity using photovoltaic panels. Both of these technologies represent powerful renewable energy solutions (Patel, 1999; Dale, 2013). However, each renewable energy source has its limitations. For wind farms, energy production depends on variable wind speeds, while solar farms generate electricity only when sunlight is available, which can also be variable. As the share of renewable energy in power systems grows, the variable nature of these sources has spurred numerous studies and analyses within both scientific research and the energy market to identify optimal technological configurations and locations for renewable energy deployment (Lopez, 2020; the E-OBS dataset from the EU-FP6 project UERRA, 2024).

This article examines the potential for optimal cooperation between wind and solar farms from the perspective of minimizing the risk of delivering a consistent amount of energy. The problem is addressed using Modern Portfolio Theory (MPT) (Markowitz, 1952; Sharpe, 1964; Castro 2022), a framework often applied in this context. However, certain critical aspects relevant to energy planning have not been fully explored in previous studies. This article seeks to fill that gap by applying the Markowitz model (MPT) to analyze the hybrid co-optimization of selected energy sources, considering both gross potential and the constraints imposed by technological capabilities.

The goal of this analysis is to determine the optimal ratio of wind and solar farm participation in energy production, with an emphasis on minimizing risk. In this context, risk is measured by the variability or dispersion in delivering a specified amount of energy.

2. Modern Portfolio Theory

Modern Portfolio Theory (MPT) is an extension of the classic Portfolio Theory first introduced in the 1950s by Harry Markowitz, who was awarded the Nobel Prize for his contributions to economics (Markowitz, 1952; Sharpe, 1964; Castro 2022). Markowitz proposed a methodology for selecting efficient investment portfolios by maximizing future expected returns for a given level of risk that investors are willing to accept. According to this theory, the characteristics of investments can be measured using only two variables: expected return and variance. Assuming that investors are risk-averse, given a choice between two investments with the same standard deviation but different expected returns, they will always choose the one with the higher expected return (and vice versa). In this way, the mean-variance model explains the benefits of diversifying investments, as it helps investors achieve a more favorable risk-return tradeoff (Markowitz, 1952; Sharpe, 1964).

The core of MPT is the mean-variance model, which helps determine efficient portfolios based on the level of risk an investor is willing to take. The model generates an efficiency curve, known as the efficient frontier, which represents different portfolios in the risk-return space. Portfolios on this curve are considered efficient because they offer the maximum expected return for a given level of risk or the minimum risk for a given expected return. Diversifying a portfolio enables an investor to reduce risk without sacrificing the expected return. As a result, investors should always select portfolios lying on the efficient frontier, as they offer the highest return for a given level of risk (Castro, 2022; Garcia, 2017; Chaves-Schwinteck, 2013).

The key insight of MPT is the identification of optimal points on the efficient frontier, allowing investors to achieve their desired level of return with minimal risk or, conversely, to minimize risk while attaining a certain expected return.

$$E(r_p) = \sum_{i=1}^{N} \omega_i E(r_i)$$

$$\sigma_p^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_i \omega_j \rho_{ij} \sigma_i \sigma_j$$

where: $E(r_p)$ – expected value of the portfolio, $E(r_i)$ – expected value of the i-th component of the portfolio, ω_i – the participation rate of the i-th component of the portfolio, σ_p^2 – portfolio variance, ρ_{ij} – correlation coefficient between the i-th, j-th components of the portfolio, σ_i – standard deviation of the i-th component of the portfolio

Investors have two alternatives when making decisions:

- **Alternative 1:** The investor, by determining the maximum level of risk they are willing to accept, can choose the optimal portfolio that maximizes the expected return for that given level of risk.

$$\max E(r_p)$$

$$\sigma_p^2 \leq \hat{\sigma}^2$$

$$\sum_{i=1}^{N} \omega_i = 1$$

$$\omega_i \geq 0$$

- **Alternative 2:** The investor, by determining the desired rate of return, can choose the optimal portfolio that minimizes the variance for that given level of expected return

$$\min \sigma_p^2$$

$$E(r_p) = \sum_{i=1}^{N} \omega_i E(r_i) = E(\hat{r})$$

$$\sum_{i=1}^{N} \omega_i = 1$$

$$\omega_i \geq 0$$

3. MPT's application to the energy market

Modern Portfolio Theory (MPT) is often applied in electricity generation planning. The mean-variance model is particularly effective for identifying optimal electricity generation portfolios. The MPT approach enables an analysis of the impact of integrating renewable technologies into the energy mix. In practice, the MPT model illustrates the trade-offs between the amount of energy produced from the mix and the associated risk, as well as between production costs and risk: generally, the lower the cost, the higher the risk (Sharpe, 1964; Castro, 2022; Garcia, 2017).

The objective of applying the mean-variance model in power generation planning is not to pinpoint a specific portfolio but to determine the efficient frontier, where optimal portfolios are located. These portfolios form Pareto-optimal sets, meaning that an increase in profits (or a decrease in costs) can only be achieved by accepting higher risk, and a reduction in risk can only be achieved by accepting higher costs.

It is important to note that a key assumption of the mean-variance model is that past events provide the best basis for predicting future outcomes. However, this assumption may be limited in the context of a rapidly evolving energy sector, where technologies and market conditions can change quickly. Therefore, despite the effectiveness of the MPT model, a flexible approach is needed when analyzing and interpreting the results, taking into account the dynamic nature of the energy industry (Chaves-Schwinteck, 2013; Fernandez, 2019; DeLlano-Paz, 2023).

In this study, we focus on two different energy mix scenarios, analyzing the potential synergies between two energy sources. In the first scenario, assuming no technological constraints, we examine the cooperation between solar and wind energy in detail. This approach allows us to better understand the optimal operating conditions of these two energy sources and how maximizing their potential can contribute to efficient electricity production. In the second scenario, we focus on the synergy between a photovoltaic power plant and a wind power plant, aiming to identify the benefits of their mutual cooperation.

4. Solar power plants

Solar radiation is constantly emitted by the Sun, which acts as a blackbody. However, not all of the solar radiation emitted by the Sun reaches the Earth's surface. Some of it is absorbed, scattered, or reflected by atmospheric particles, and it can also change direction and intensity due to interactions with clouds and other atmospheric elements. The intensity of solar radiation is measured in watts per square meter [W/m^2] (Patel, 1999; DeLlano-Paz, 2023; Cornes, 2018; Silva, 2022). The total amount of radiation per unit area that reaches the Earth's surface over a given period, typically one day, is referred to as Global Horizontal Irradiance (GHI). GHI data collected over one or more years is crucial for assessing the potential for photovoltaic power generation at a specific location. Photovoltaic power generation involves converting solar radiation into electricity through the photovoltaic effect. Solar power plants, commonly referred to as solar farms, consist primarily of photovoltaic panels. Increasingly, solar farms are being integrated with other renewable energy sources, forming hybrid systems. Integrating solar farms with wind farms or energy storage systems enhances the flexibility and reliability of the overall energy system.

The analysis assumed a photovoltaic farm with an installed capacity of 1 [MW$_p$]. The panel power was calculated from the following formula.

$$P_{\text{out}} = \eta P_{STC}\left(\frac{R_{\text{hor}}}{R_{STC}}\right)\left[1-\alpha_p\left(T_m - T_{STC}\right)\right]$$

where: P_{out} – panel output power [W], $\eta = 0.85$, P_{STC} – nominal panel power PV [W], R_{STC} = 1000 [W/m^2] under test conditions (Standard Test Conditions, STC), T_m – operating temperature [°C], $T_{STC} = 25$ [°C] – reference temperature, under test conditions (STC).

Ultimately, it was adopted:

$$P_{\text{out}} = 0.225 R_m \left[1 - 0.0042\left(T_m - T_{STC}\right)\right]$$

where: R_m – the total solar radiation (direct, reflected, and diffuse) [W m^{-2}].

5. Wind turbines

Wind turbines harness the energy of the wind (specifically, the kinetic energy of moving air masses) and convert it into useful energy, typically mechanical or electrical. The devices responsible for this conversion are known as wind turbines. Energy conversion occurs when the wind passes through the area swept by the rotor of the turbine. The rotor blades are aerodynamically designed to move in a direction perpendicular to the wind flow, capturing a portion of the kinetic energy available in the moving air.

The amount of energy harnessed from the wind depends on its speed and density. However, not all of the kinetic energy in the wind can be converted into usable energy as it passes through a wind turbine. The ratio of the kinetic energy that can be converted by the wind turbine to the total available kinetic energy in the wind is called the power coefficient (C_p). The maximum theoretical value of the power coefficient for a wind turbine is 16/27 (or 59.3%), as dictated by Betz's law (Fig. 1). This means that a wind turbine can convert up to 59.3% of the kinetic energy available in the wind into mechanical energy. The actual output power of a wind turbine varies with wind speed and is calculated using a specific equation (Patel, 1999; Dale, 2013).

$$P_{\text{out}} = \frac{1}{2} C_p \rho A V^3$$

where: P_{out} – is the output power [W], C_p – power factor, ρ – air density [kg/m^3], A – he surface swept by the rotor blades [m^2], V – wind speed [m/s].

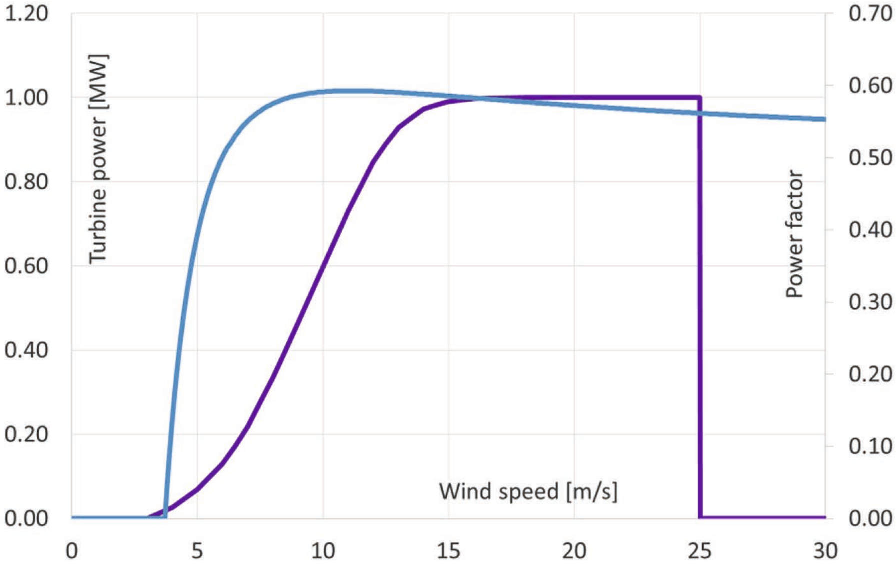

Fig. 1. Power curve and power factor of a wind turbine (own elaboration)

Both the power coefficient (C_p) and the power output of a wind turbine depend on wind speed (Patel, 1999). The performance of a wind turbine is typically represented by its power curve, which shows the exact power output the turbine can generate at different wind speeds (Patel, 1999; Dale, 2013). The cut-in speed refers to the minimum wind speed required to generate enough energy to start the rotor blades moving from a stationary position. The rated output speed is the wind speed at which the turbine reaches its maximum power output, also known as its rated power. Beyond this speed, the output power remains constant at the rated level, even if the wind speed increases. However, when wind speeds exceed the cutoff speed, the turbine must be shut down to prevent damage. A wind turbine's power curve, typically provided by the manufacturer, serves as a visual representation of its performance and power output at varying wind speeds (Patel, 1999).

6. Data used in the analysis

The analysis presented in this article is based on daily gridded data from published products of the National Oceanic and Atmospheric Administration (NOAA) and the European Union's Earth Observation Program (DeLlano-Paz, 2023; Cornes, 2018). The data used in the analysis have a spatial resolution of 0.25° × 0.25° and are accessible via the Internet, although they are not available in real time.

The study utilized data that characterize the potential of wind energy (Fig. 2, 6, and 7), solar energy (Fig. 4 and 5), and temperature (Fig. 3, 5, and 6).

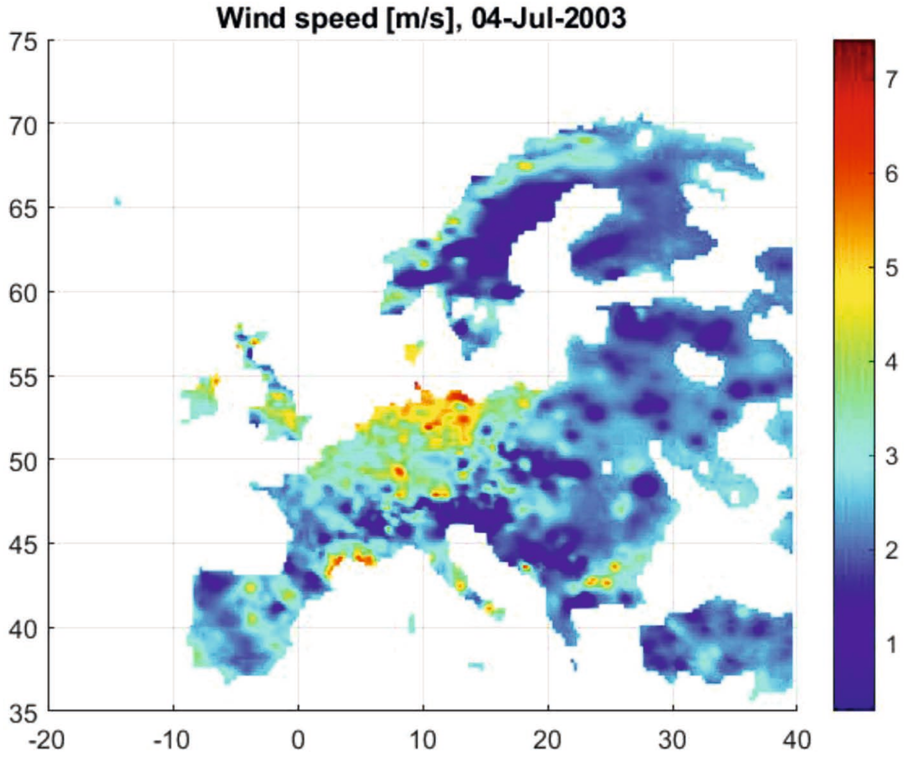

Fig. 2. Average daily wind speed for 2023-07-04 (own elaboration)

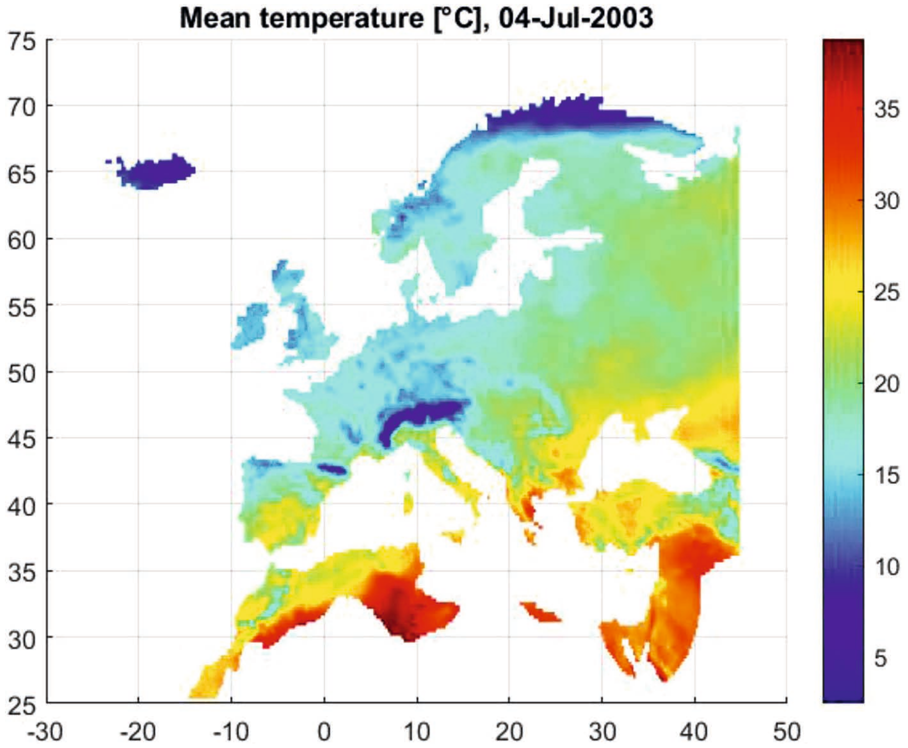

Fig. 3. Average daily temperature for 2023-07-04 (own elaboration)

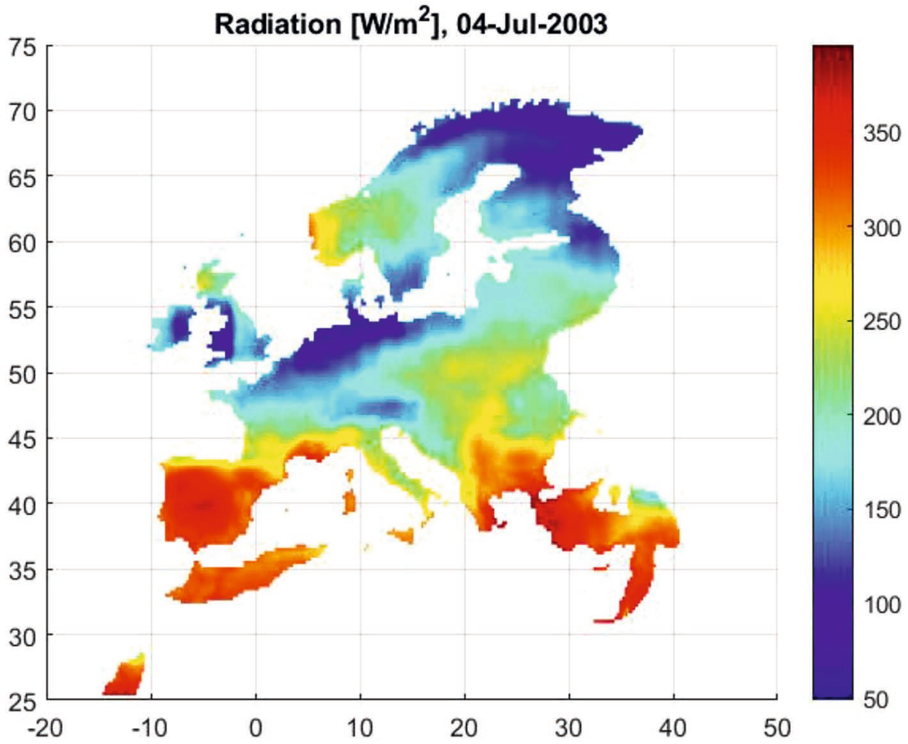

Fig. 4. Average daily radiation for 2023-07-04 (own elaboration)

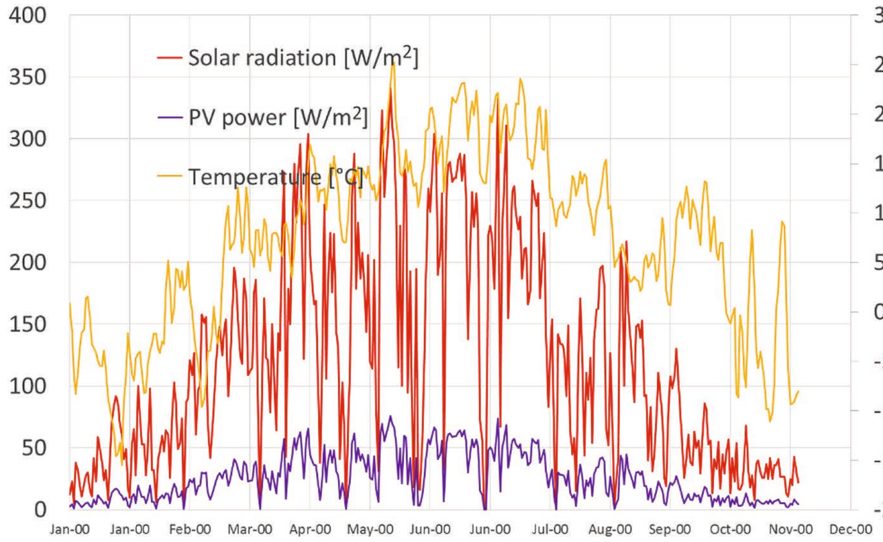

Fig. 5. Variability of temperature, solar radiation and PV power obtained, geographic coordinates (22.375, 49.375), year 2010, Poland (own elaboration)

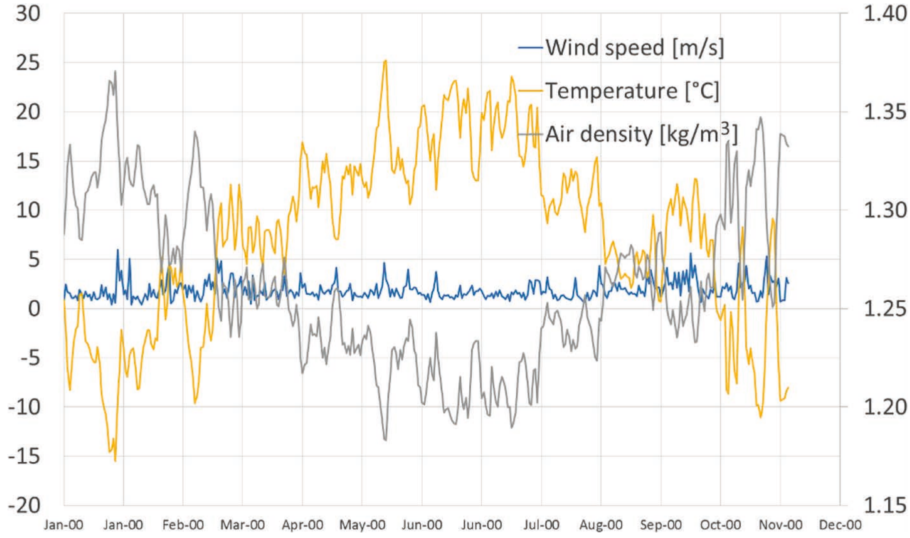

Fig. 6. Variability of temperature, wind speed and air density as a function of temperature, geographic coordinates (22.375, 49.375), year 2010, Poland (own elaboration)

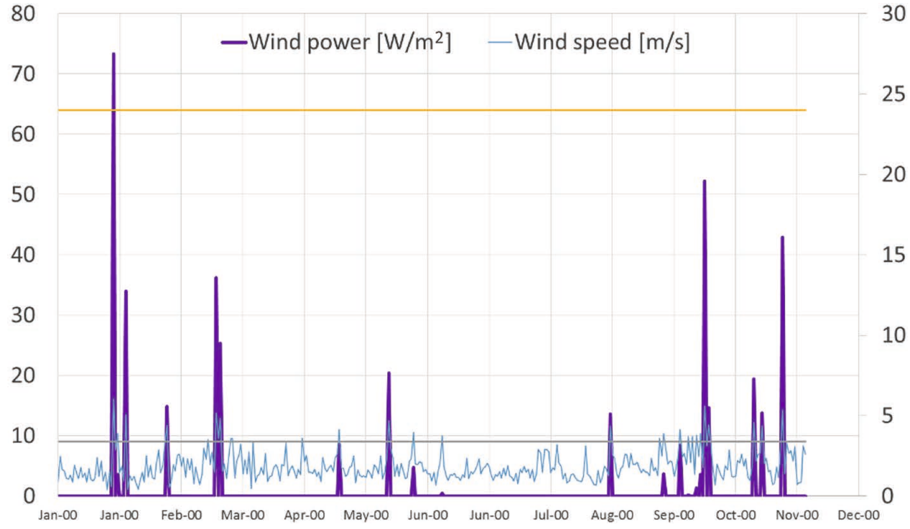

Fig. 7. Variability of wind speed and wind turbine power output, geographic coordinates (49.375, 22.375), year 2010, Poland (own elaboration)

7. The idea of energy cooperation – synergy

Wind and solar power are considered variable renewable energy sources. They have two main disadvantages: first, unlike fossil or nuclear fuels, they cannot be transported to another location, and second, the high variability of solar radiation and wind speed over time leads to fluctuations in power output. Consequently, these energy sources must be transported to end users in the form of electricity via the grid, which involves transmission and distribution losses (Ceran, 2017). Hybrid photovoltaic (PV) and wind systems combine the use of photovoltaic panels and wind turbines to maximize total energy production and improve system efficiency. The variability in solar and wind energy makes it challenging for these systems to meet demand when operating independently. Additionally, the uncertainty in forecasting these resources introduces further constraints, making it difficult to match energy production with demand accurately. However, the complementarity of solar and wind resources makes combining them an attractive solution for reducing power generation variability. The integration of solar and wind power in hybrid systems mitigates the variability of each individual system, thereby enhancing overall system performance and reliability (Kowalczyk, 2022; Ceran, 2017; Wyrobek, 2018).

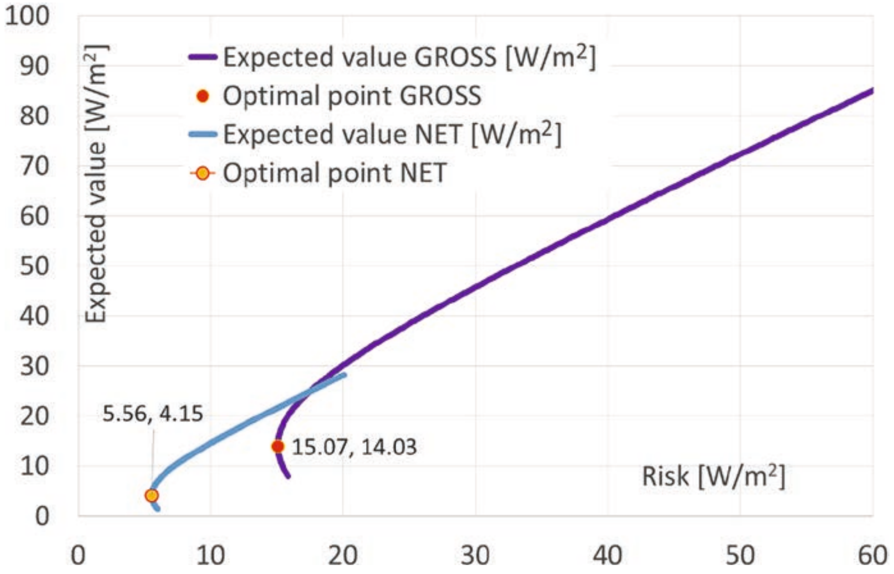

Fig. 8. Change in location of optimum point after introduction of technological solutions compared to solar and wind potential, geographic coordinates (49.375, 22.375), year 2010, Poland (own elaboration)

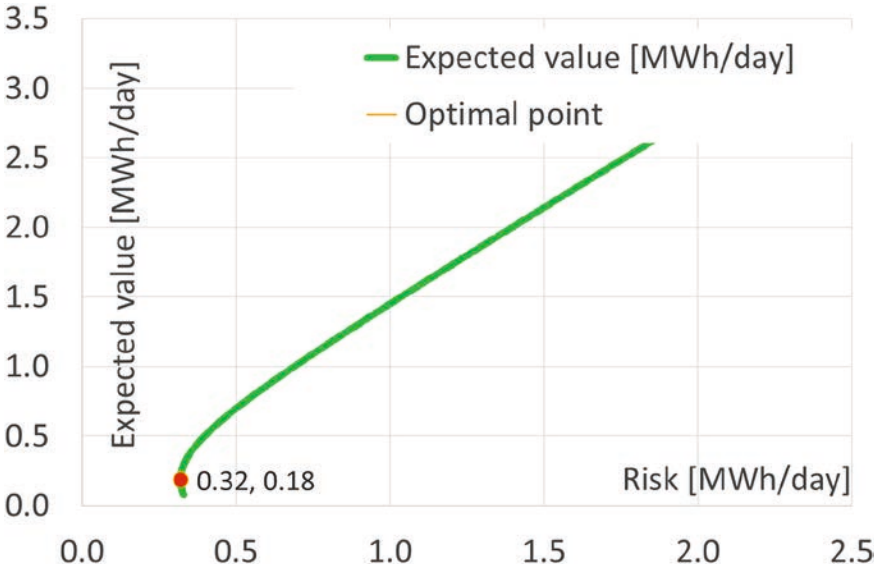

Fig. 9. Optimal point on the example of analysis of daily production volume of 2 MW energy mix, geographical coordinates (49.375, 22.375), year 2010, Poland (own elaboration)

This example illustrates the application of MPT in energy co-option analysis. A detailed analysis of the energy potential (gross) available at a given location (risk: 15.07 $[W/m^2]$, expected value: 14.03 $[W/m^2]$) was conducted for data on solar radiation, wind speed and temperature (Fig. 8). The introduction of modern technological solutions in the form of a hybrid power plant with components: a photovoltaic (PV) plant and a wind power plant with a capacity of 1 [MW] each, made it possible to convert this potential into electricity (Fig. 8, 9). However, the results of the analysis indicate a significant reduction in electricity production (net) (risk: 5.56 $[W/m^2]$, expected value:4.15 $[W/m^2]$) compared to the available potential (gross). As part of the analysis, a risk-minimizing approach was adopted, which made it possible to identify the optimal points for the technologies used in the hybrid energy mix. As a result, the efficiency of the obtained amounts of electricity using PV and wind power reached a level of about 29.5% (4.15 $[W/m^2]$/14.03 $[W/m^2]$) in relation to the available potential. For the 2 [MW] energy mix concept, the following parameters of a 1 $[MW_p]$ PV power plant were adopted: a 225 $[W/m^2]$ PV cell (STC). For the wind power plant solutions, the parameters of a 1 [MW] turbine from LM Glasfieber with an active blade area of 2290.0 $[m^2]$ were adopted.

8. Map of optimal values

The analysis presented in the chapter on cooperation was conducted for the entire area of Poland. The results include maps showing the optimal participation rates between the components of the hybrid power system across Poland (Fig. 10). Additionally, maps of minimum risk values (Fig. 11) and maps illustrating the potential for achieving expected power values (Fig. 11) were provided for both energy potential (gross) and energy production from the energy mix (net).

When analyzing the maps of wind energy participation rates, it is important to note that the solar energy participation rate complements the wind energy rate, with the sum equaling 1. The greatest wind energy potential is concentrated in northwestern and northeastern Poland, while the central regions of the country are not particularly distinguished by this form of energy.

Regarding the maps showing the expected power output per square meter $[m^2]$, it should be highlighted that the efficiency of energy recovery (net/gross) reaches a maximum of around 40%. The expected value of net power output is approximately 80 W/m^2, while the gross power value reaches about 30 W/m^2, with a minimum risk value around one-third of these Figures.

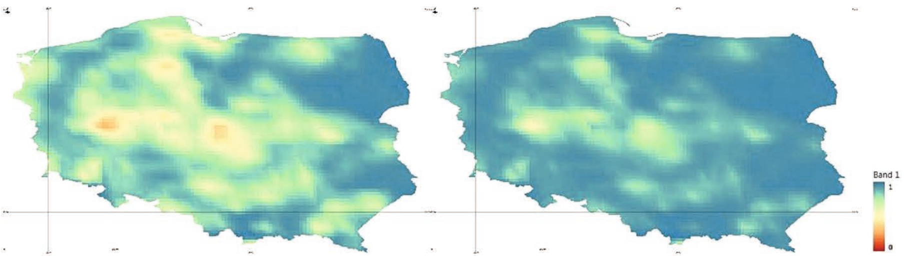

Fig. 10. The value of optimal coefficients for the share of the wind energy component in the energy mix: a. gross, b. net, year 2010, Poland (own elaboration)

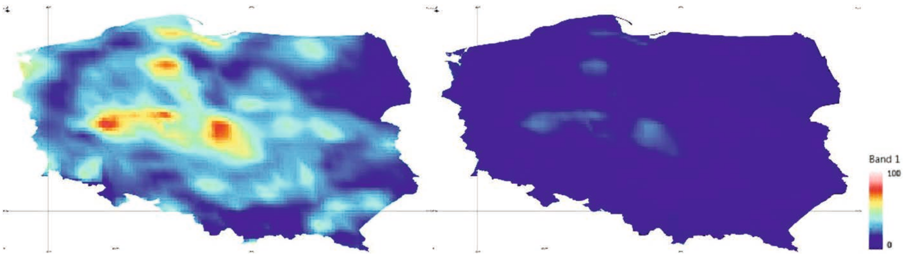

Fig. 11. The value of optimal expected values of obtained power from the energy mix $[W/m^2]$: a. gross, b. net, year 2010, Poland (own elaboration)

The analysis is based on data from the year 2010, which, in terms of climatic conditions for solar and wind energy, was not an outlier. This underscores the overall scarcity of renewable energy resources (RES) in Poland.

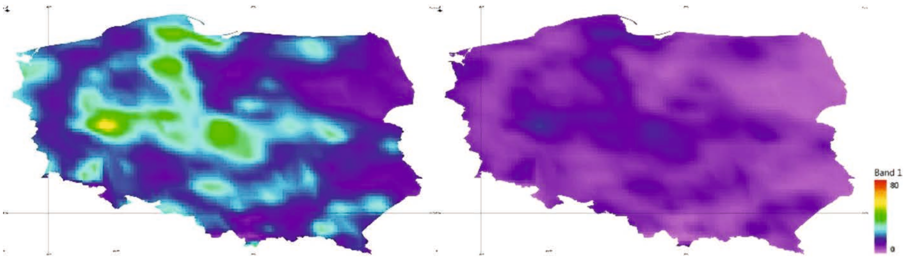

Fig. 12. Value of optimal (minimum) values of the risk of obtaining power from the energy mix [W/m²]: a. gross, b. net, year 2010, Poland (own elaboration)

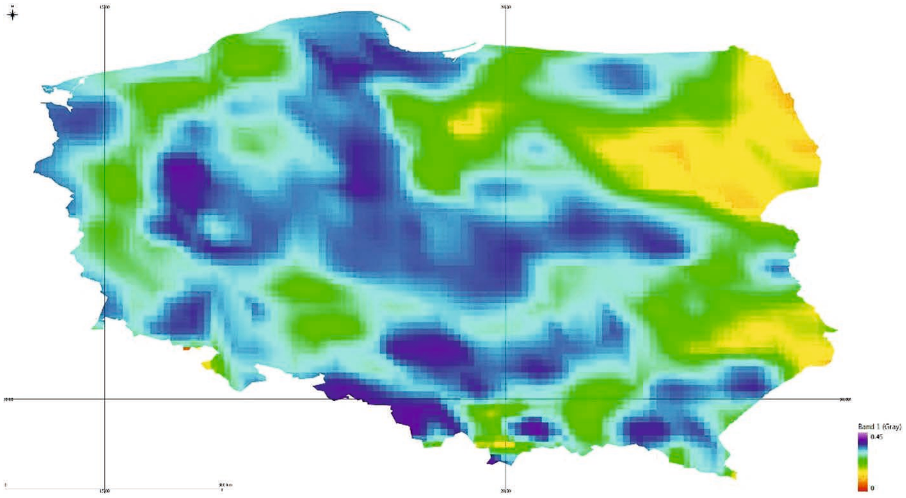

Fig. 13. Efficiency of technological solutions in relation to potential, 2010, Poland (own elaboration)

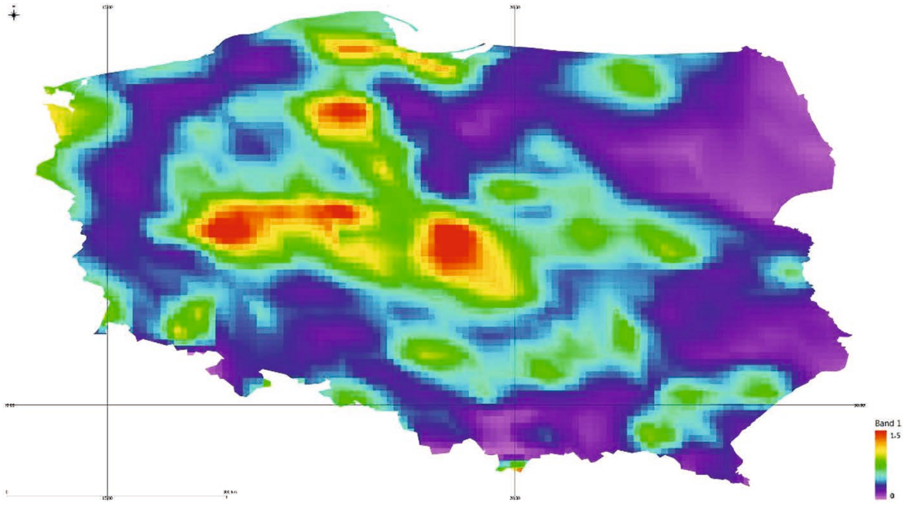

Fig. 14. Optimal daily electricity production [MWh/day] from a mix of a wind power plant of 1 [MW] and a solar power plant also of 1 [MW], year 2010, Poland (own elaboration)

9. Economic analysis

Maps of expected power values obtained from 1 [m²] show that energy recovery efficiency (net/gross) oscillates around a level of up to 40% at most. The expected gross power value reaches 80 [W/m²] while the net value reaches 30 [W/m²] with a minimum risk of about 1/3 of these values. The efficiency of the solutions (Fig. 13) is mainly built on the solar component. Analyzing the magnitudes of optimal production calculated as the expected value of electricity produced with minimal risk from a hybrid power plant with a capacity of 2 [MW], it is possible to obtain an annual revenue of 0.45 [million/year] at an average price for energy of 821 [PLN/MWh] (Fig. 14). With an investment cost of the order of 10 [PLN 1e6] and annual operating costs of 0.25 [PLN 1e6], the return on investment at current prices extends over 40 years.

Table 1. Wind power plant expenditures 1 [MW], data year 2022

Expenditures	%	Amount tys. PLN
Cost of the turbine	81.5%	5 500
Roads and foundations	7.4%	500
Cost of connection	5.9%	400
Design costs	3.7%	250
Cost of internal electrical network	1.5%	100
	100%	6 750

Table 2. Solar power plant expenditures 1 [MW], data year 2022

Installation cost	%	Amount tys. PLN
Design documentation	2.3%	84.64
Photovoltaic modules	45.4%	1 692.83
Inverters	4.5%	169.28
Supporting structure	9.1%	338.57
DC and AC cable lines and protection	4.0%	148.12
Transformer station	9.7%	359.73
Medium voltage connection	3.4%	126.96
Fencing	2.0%	74.06
Elements depending on the decision and requirements of the investor, e.g. video and technical monitoring, lighting, access roads	2.8%	105.80
	100%	3 100

Table 3. Operating cost of 2[MW] power plant, data year 2022

Operating cost	%	Amount tys. PLN
Maintenance, management	51	131.58
Property tax/rent payments	18	46.44
Energy balancing	16	41.28
Insurance	10	25.80
Energy for own use	5	12.90
	100.0	258.00 zł

Calculating the investment costs for a wind and solar power plant mix yields an amount of approximately 9.85 million PLN. Taking into account the annual operating costs of 0.25 million PLN, it is possible to estimate the average electricity sale price from renewable energy auctions that would cover these operating expenses (Tables 1–3). Assuming an expected daily production value, with minimal risk, of 1.5 MWh, the minimum average sale price of electricity from renewable auctions should be around 490 PLN/MWh. This is significantly higher than the average auction price of 375 PLN/MWh, which was achieved in 2022. It is important to note that these analyses apply only to areas with the highest energy recovery potential, specifically central Poland. The analysis does not yet account for profit or the investment payback period. In the current market conditions, the potential profit from such an investment can be compared to winning a lottery. The results highlight the need for much higher EU investment support than is currently proposed, as achieving profitability without this support is challenging. Eurostat data show that the most profitable wind energy production appears to be in Austria, Belgium, Portugal, and the United Kingdom. Germany is an exception, where despite high electricity prices, many wind farms are incurring losses (Ec. Europa, online).

10. Conclusion

In this study, the Markowitz model was applied to analyze the energy mix consisting of wind and solar power plants. By analyzing solar radiation, temperature, and wind speed, the optimal contribution factors for wind and solar energy components (gross) and for wind and solar power plant components (net) were calculated for Poland, assuming a capacity of 1 MW for each component. The calculations allowed for the assessment of the technological efficiency, determination of minimum risk values, and expected power output at these minimum risk levels. The greatest wind energy potential is concentrated in northwestern and northeastern Poland, while central Poland is not rich in wind energy resources, in contrast to solar energy. This highlights the need to reassess the viability of investing in wind energy in certain regions. Photovoltaic investments have a return on investment (ROI) of around 8%, which suggests the need for reinvestment in these installations before the total payback period is reached. Given these analyses and the profitability parameters of these investments, the only viable direction for expanding the energy mix includes sources such as biogas plants, hydropower, and investments in nuclear energy.

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